State-of-the-art Shielding Design and Simulations for Proton, Electron and Ion Beams

Nikolai Mokhov, Fermilab

International Workshop on FFAGs
Fermilab
September 21-25, 2009

OUTLINE

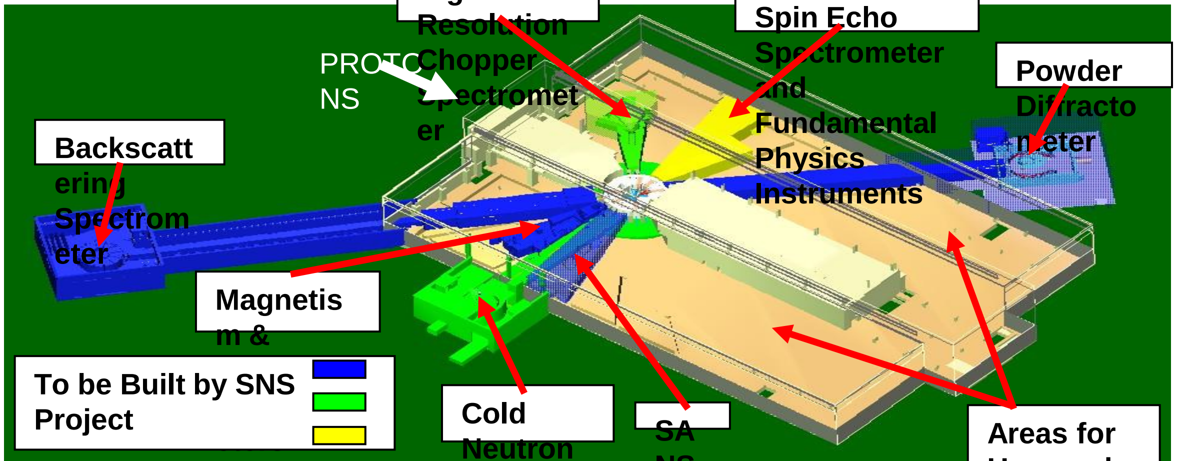
- Introduction
- Application Examples & Demands
- General Purpose All-Particle Codes
- Benchmarking (focusing on ion beams)
- Advances in Code Developments
- Recent Proton, Electron and Ion Beam Applications
- Summary

INTRODUCTION

Requirements to particle transport simulation tools and needs for physics model and calculation code developments are **all driven by application**. The most demanding among them are high-power accelerators (Spallation Neutron Source, J-PARC, neutrino factories), heavy-ion and ADS facilities (FRIB, FAIR, EURISOL), high-energy colliders (LHC, ILC), medical beams and space exploration.

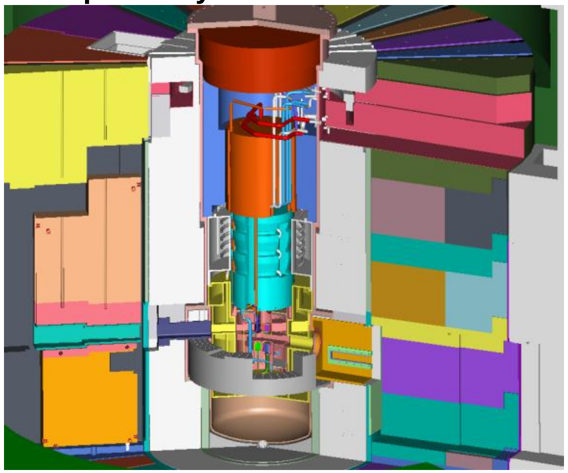
Feasibility, design and specific radiation issues are addressed in detailed Monte-Carlo simulations, therefore, **predictive power and reliability** of corresponding codes are absolutely crucial.

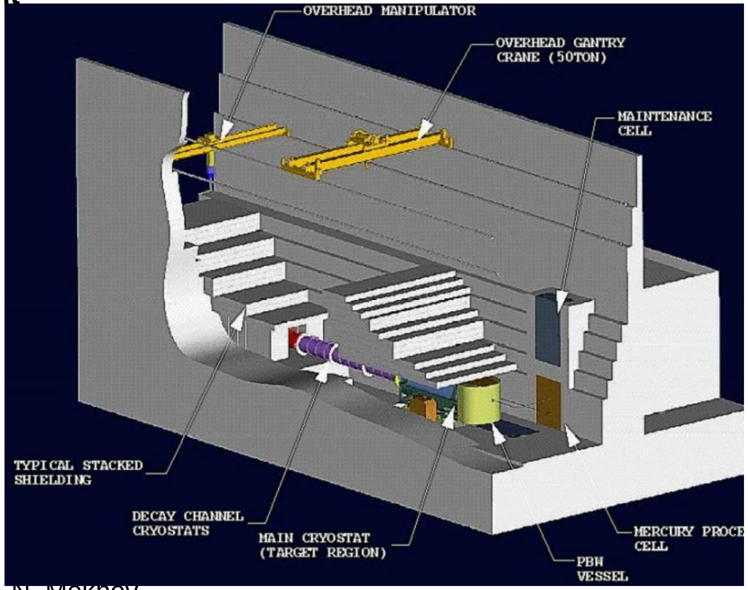
SNS & Neutrino Factory High-Power Target Buildings



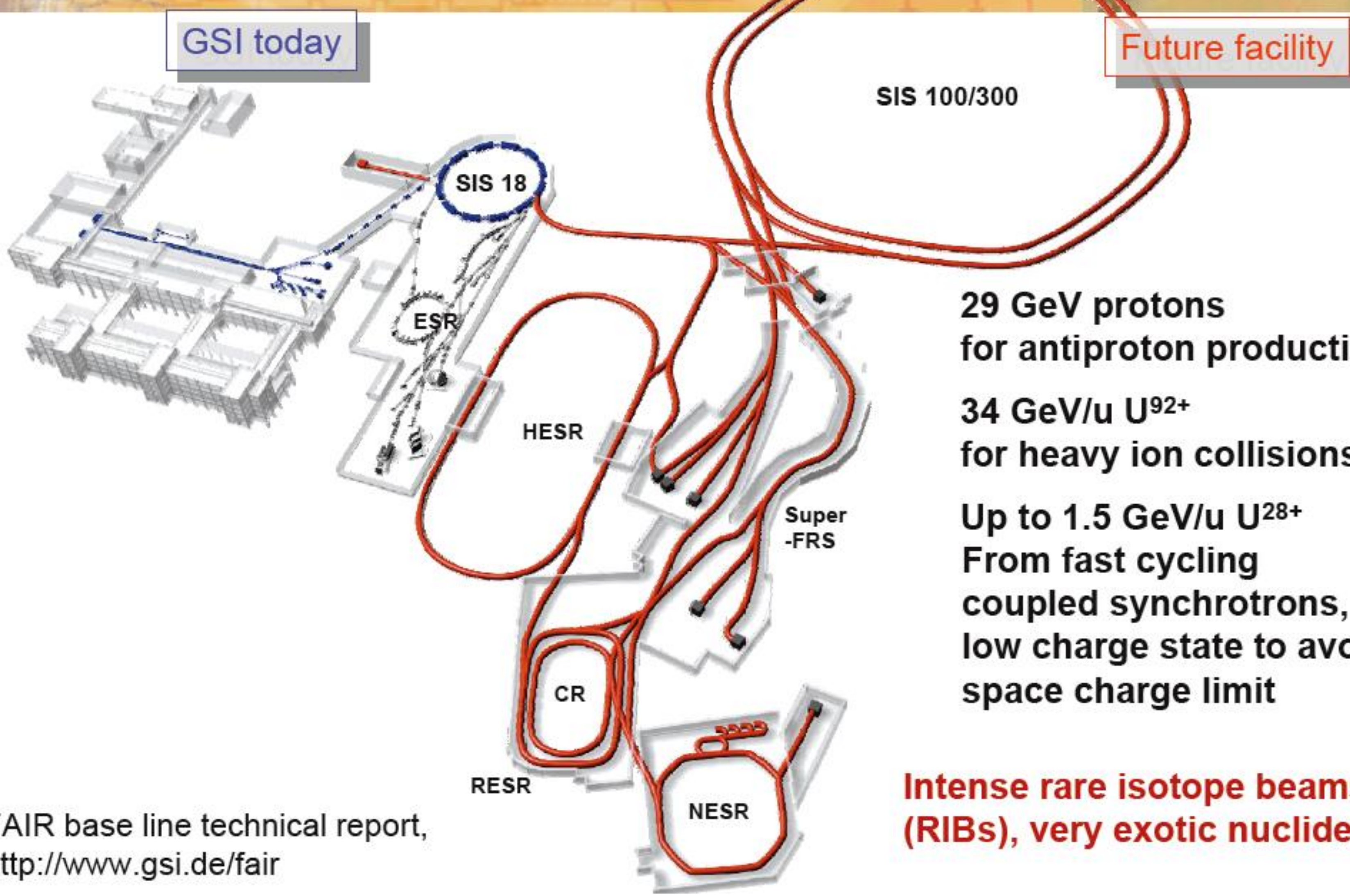
To be Built by IDTs

Proposed by IDTs





FAIR - Facility for Antiproton and Ion Research



29 GeV protons for antiproton production

34 GeV/u U^{92+} for heavy ion collisions

Up to 1.5 GeV/u U^{28+} From fast cycling coupled synchrotrons, low charge state to avoid space charge limit

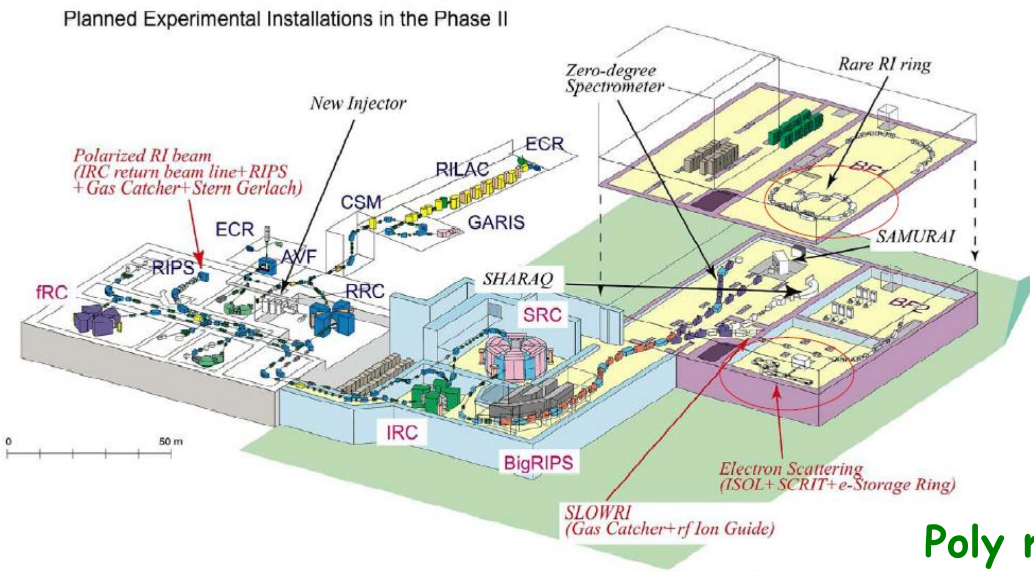
Intense rare isotope beams (RIBs), very exotic nuclides

FAIR base line technical report, http://www.gsi.de/fair

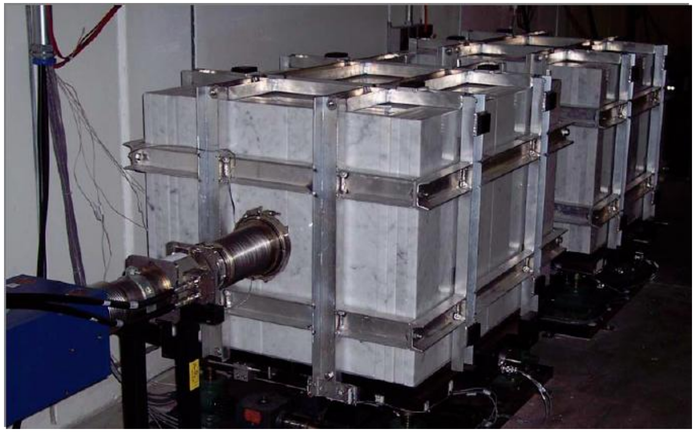
RIB-factory & Main Injector Collimators

RIKEN RIB-factory

Precision mass measurement with accuracy of ppm for 1 particle/day RI ions (Rare RI ring)



Electron scattering off RI ions using Self-Confining RI ion Target (SCRIT)



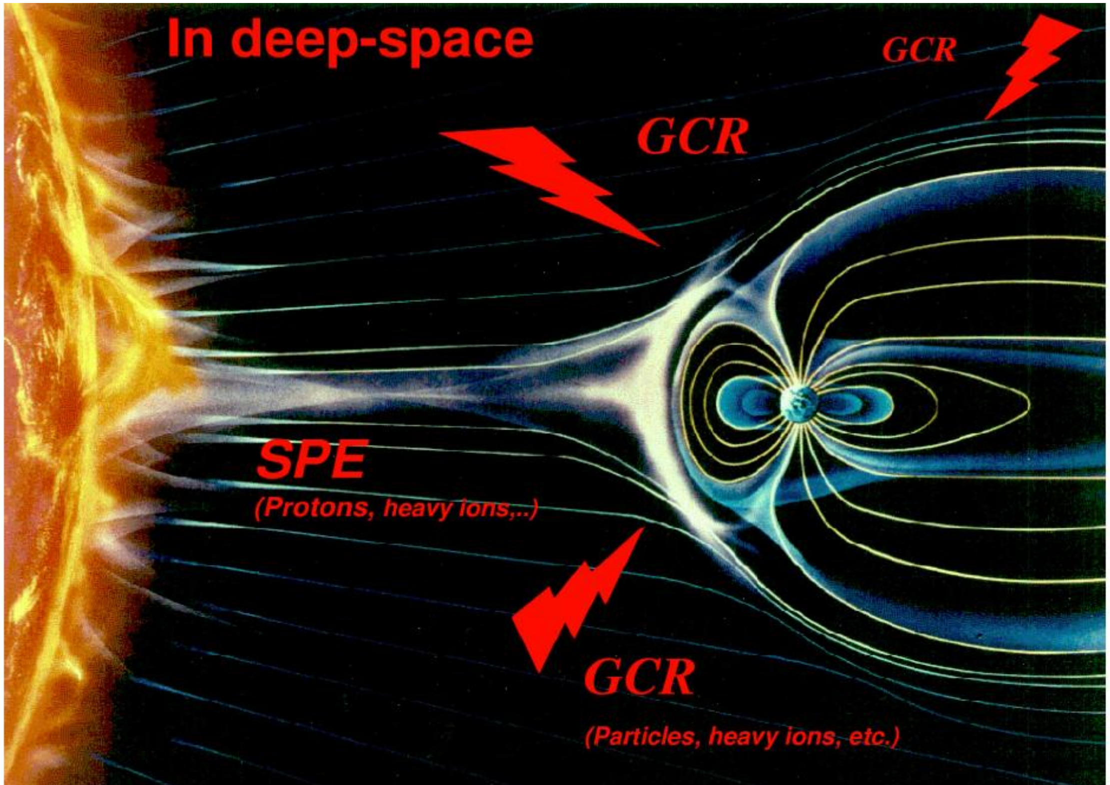
Marble shells of a brand-new collimation system at Fermilab MI

Poly mask

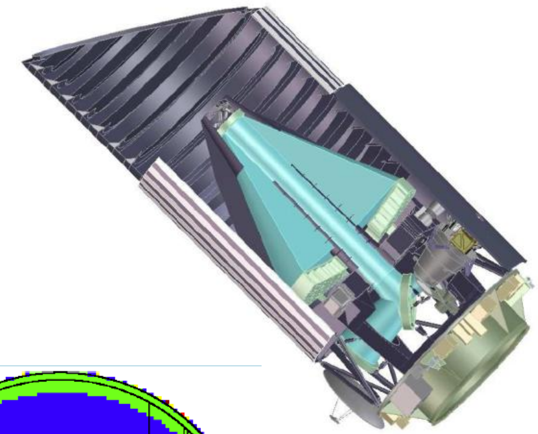
Design optimization via MC calculations:

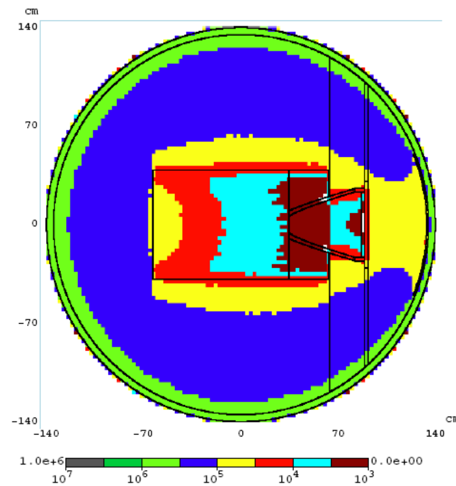
Prompt radiation, residual radiation (hands-on maintenance), air, ground & sump water activation, beam-induced damage (heating, material integrity, component lifetime), etc.

SPACE APPLICATIONS



Adapted from: L. Sihver "Benchmarking of the particle and heavy ion transport codes", International Conference on Nuclear Fragmentation, September 24 - October 1, 2007, Kemer,Turkey, http://fias.uni-frankfurt.de/nufra2007/





MARS-calculated charge transfer efficiency degra-dation in CCD: 60% at the end of 4-year SNAP mission

Space radiation protection is one of five critical enabling technologies identified in the NASA Strategic Plan for human space exploration. Issues: knowledge of galactic, solar and trapped radiation; astronaut and electronics (SEU!) protection weight constraints; low-dose biological effects; accuracy of particle and heavy-ion transport physics, etc.

PARTICLE INTERACTION AND TRANSPORT CODES

Only with a very **reliable and accurate simulation code** based on modern physics models and data can one perform computer modeling to meet the needs of the applications described.

Five **general-purpose all-particle** codes, extensively used worldwide in accelerator and space applications, are in this category.

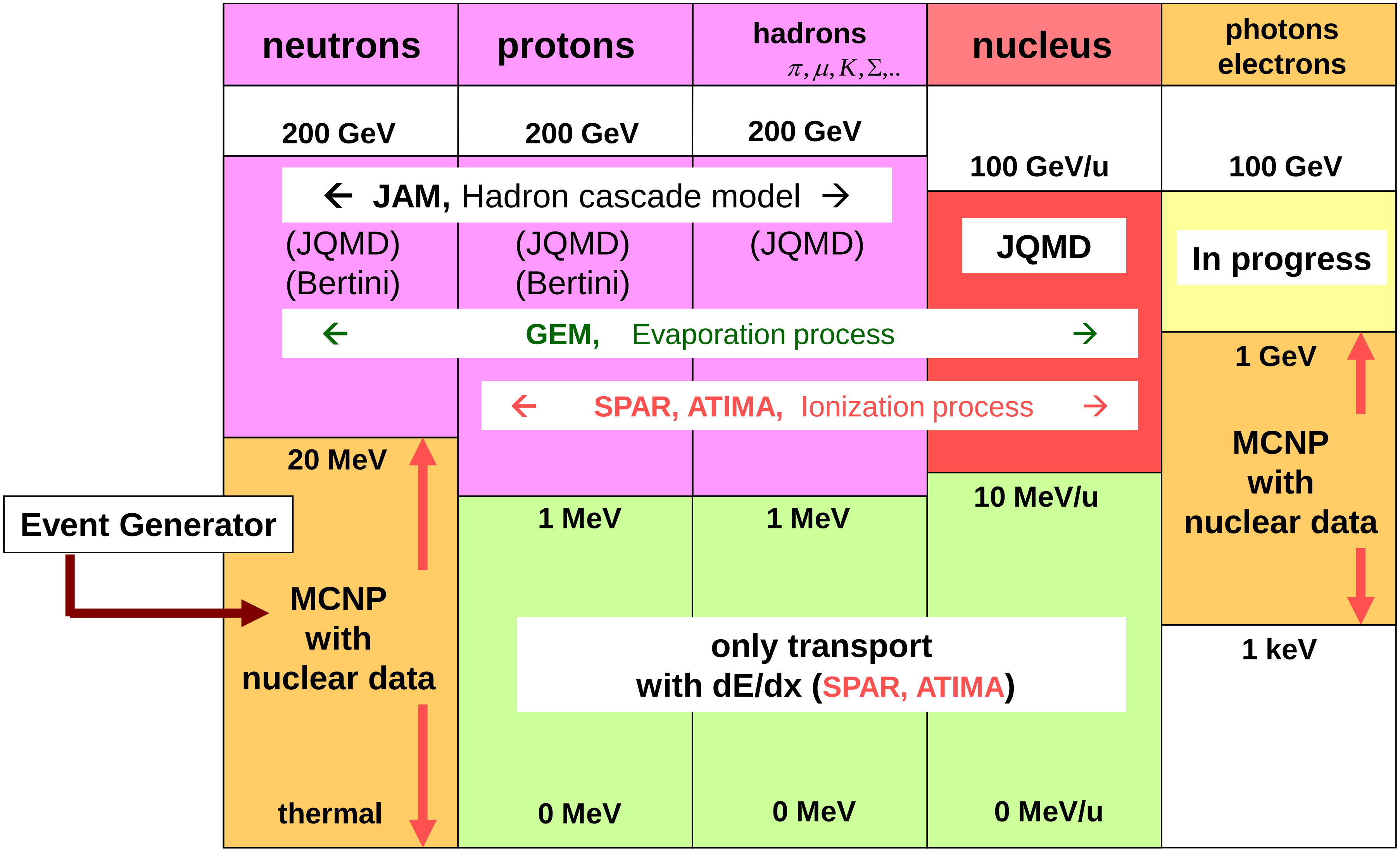
GENERAL PURPOSE ALL-PARTICLE CODES

1. **FLUKA*** – since 1970, currently FLUKA-2008.3b.1, CERN & INFN
2. **GEANT** – since 1974, currently GEANT4-9.2, CERN, SLAC et al.
3. **MARS*** – since 1974, currently MARS15 (2009), FNAL
4. **MCNPX** – since 1994, originated from earlier MCNP, currently MCNPX-2.6.0, LANL
5. **PHITS*** – since 2003, currently PHITS-2.15, JAEA, RIST, KEK

Particle energies from hundreds TeV (FLUKA, GEANT, MARS) down to thermal neutron energy, **10^{-3}<E<10^{14} eV**.

(*) Well tuned for ion beams.

EXAMPLE: PHISICS CAPABILITIES IN PHITS

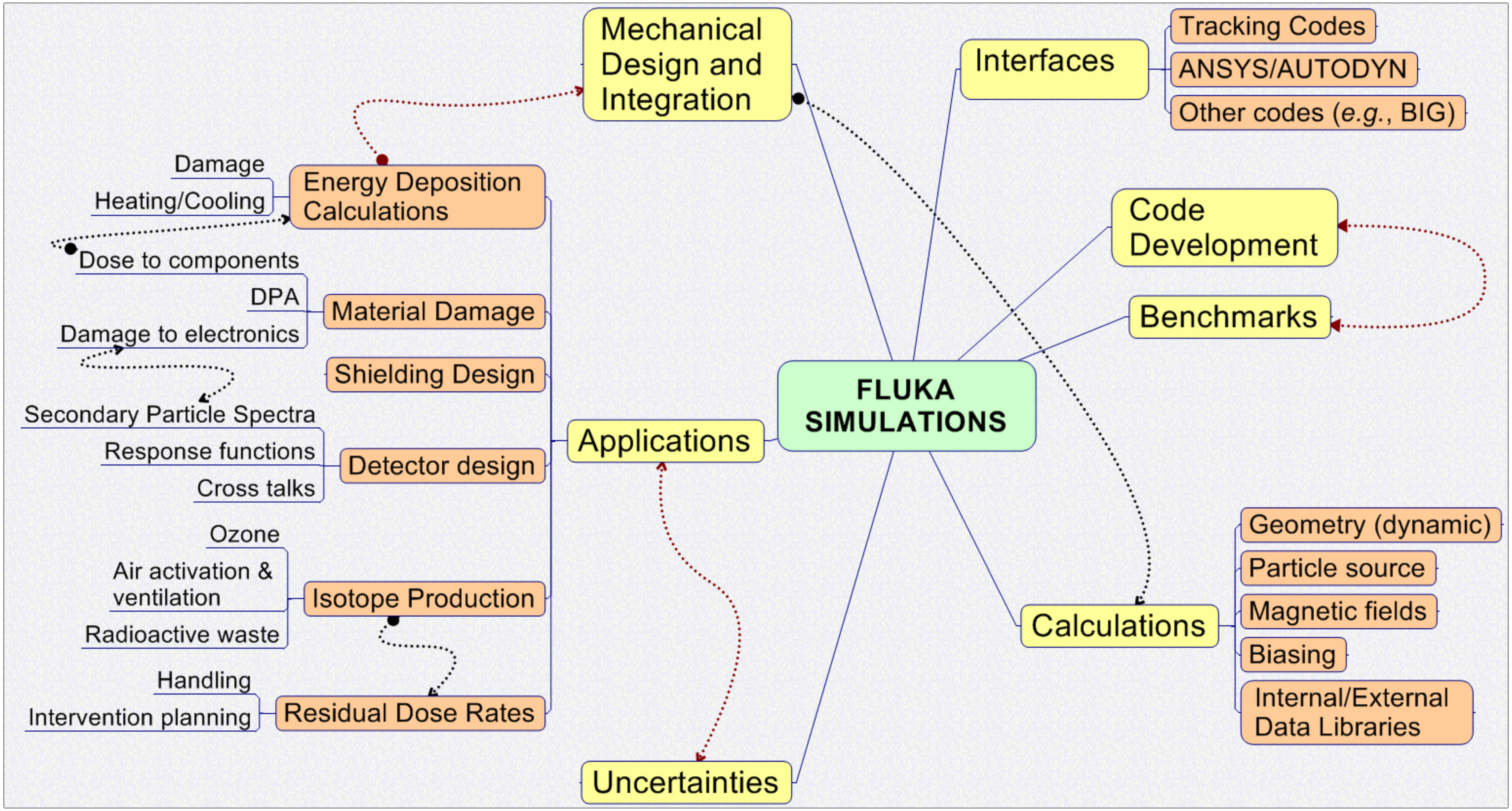


CODE FEATURES

All five codes can handle very complex geometries, have powerful user-friendly built-in GUI with magnetic field & tally viewers, and variance reduction capabilities.

Tallies include volume and surface distributions (1D to 3D) of particle flux, energy, reaction rate, energy deposition, residual nuclide inventory, prompt and residual dose equivalent, DPA, event logs, intermediate source terms, etc.

Code Multifold Structure: e.g., FLUKA & MARS



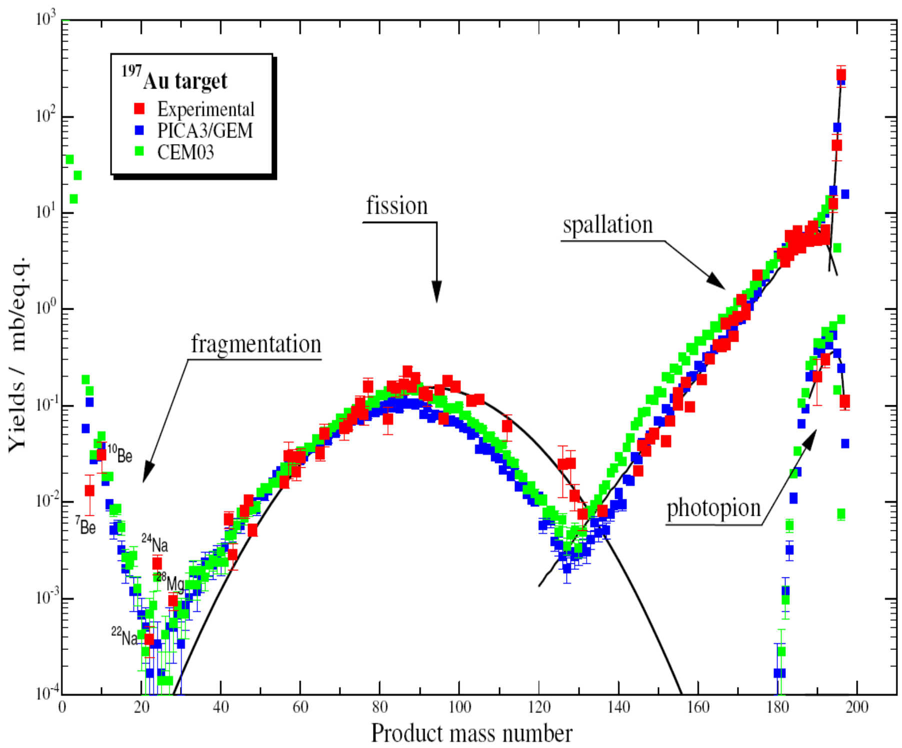
MARS15 EXCLUSIVE EVENT GENERATORS

Improved Cascade-Exciton Model code, **CEM03.03**, combined with the Fermi break-up model, the coalescence model, and an improved version of the Generalized Evaporation-fission Model (GEM2) is used as a default for hadron-nucleus interactions below 3 GeV. Recent multi-fragmentation extension.

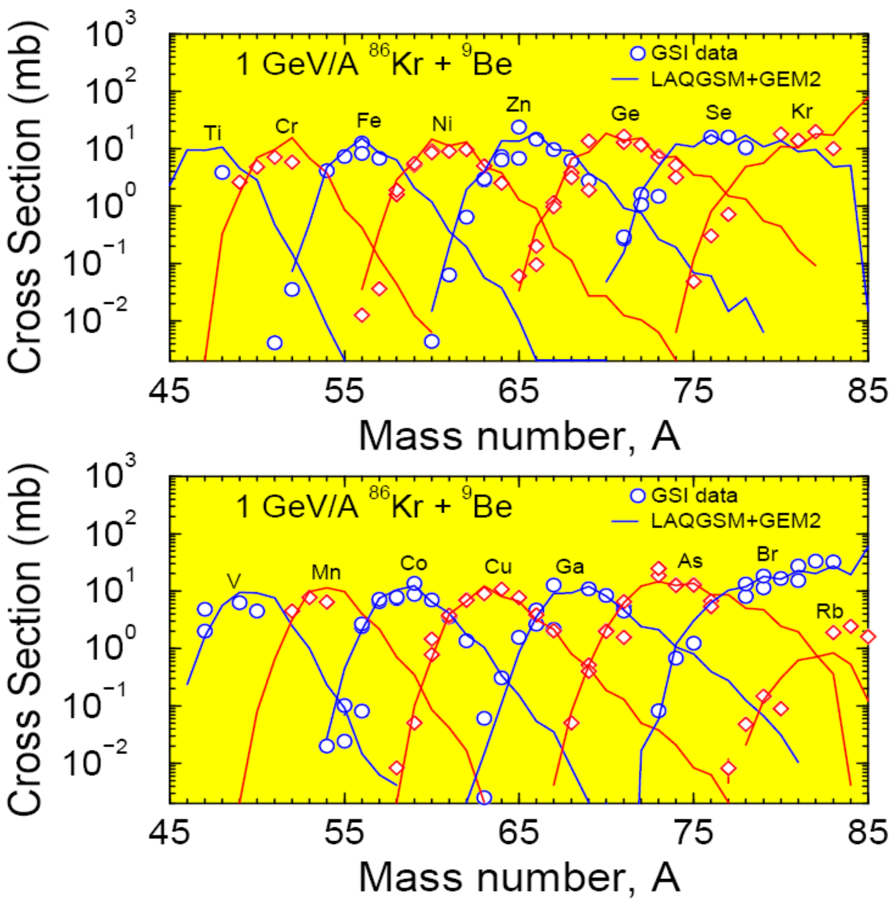
The Quark-Gluon String Model code, **LAQGSM03.03 (2009)**, is used in MARS15 for photon, particle and heavy-ion projectiles at a few MeV/A to 1 TeV/A. This provides a power of full theoretically consistent modeling of exclusive and inclusive distributions of secondary particles, spallation, fission, and fragmentation products.

Benchmarking: NUCLIDE PRODUCTION

Bremsstrahlung (Emax=1 GeV) on gold

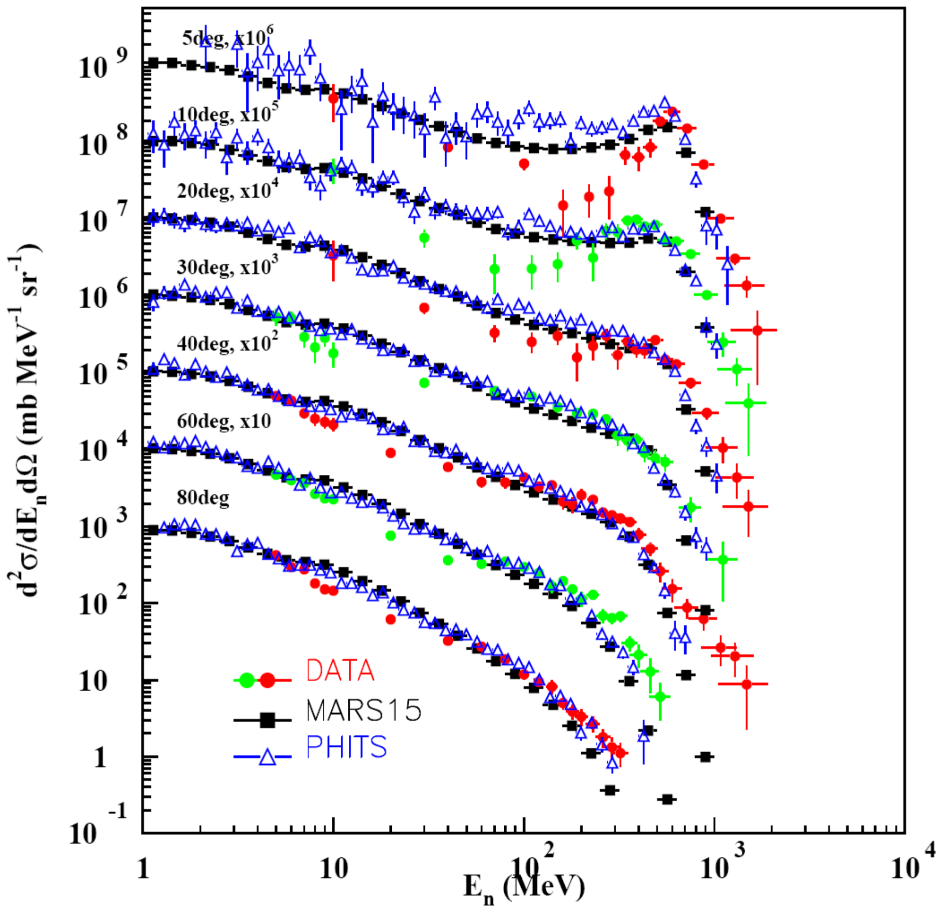


1 GeV/A ^{86}Kr on ^{9}Be

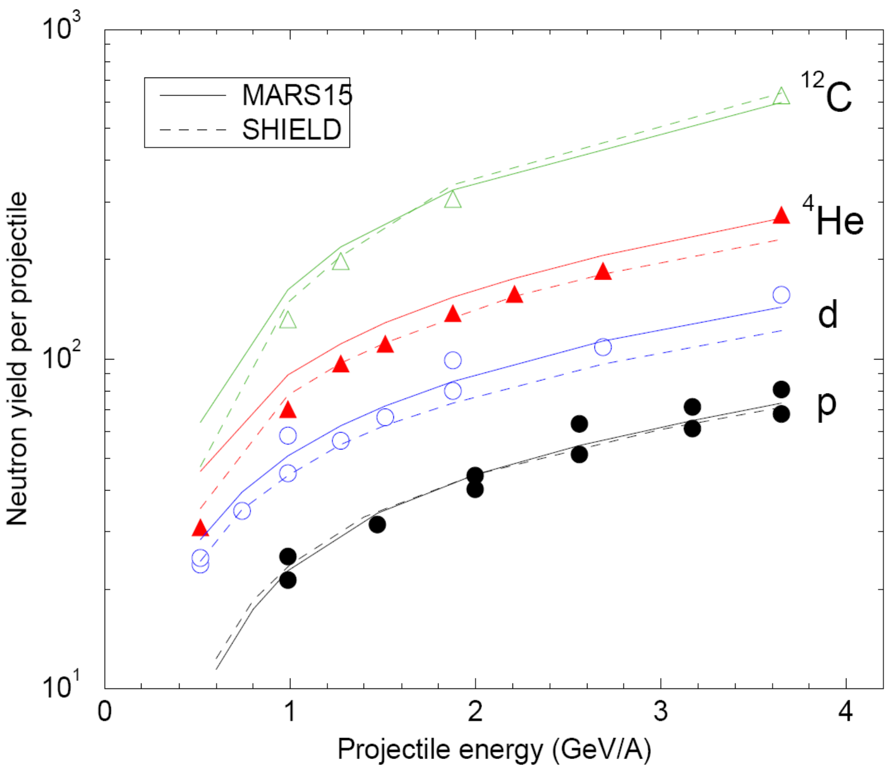


Neutron Yield from Lead Targets for Heavy-Ion Beams

600-MeV/A Ne on 4-mm Lead



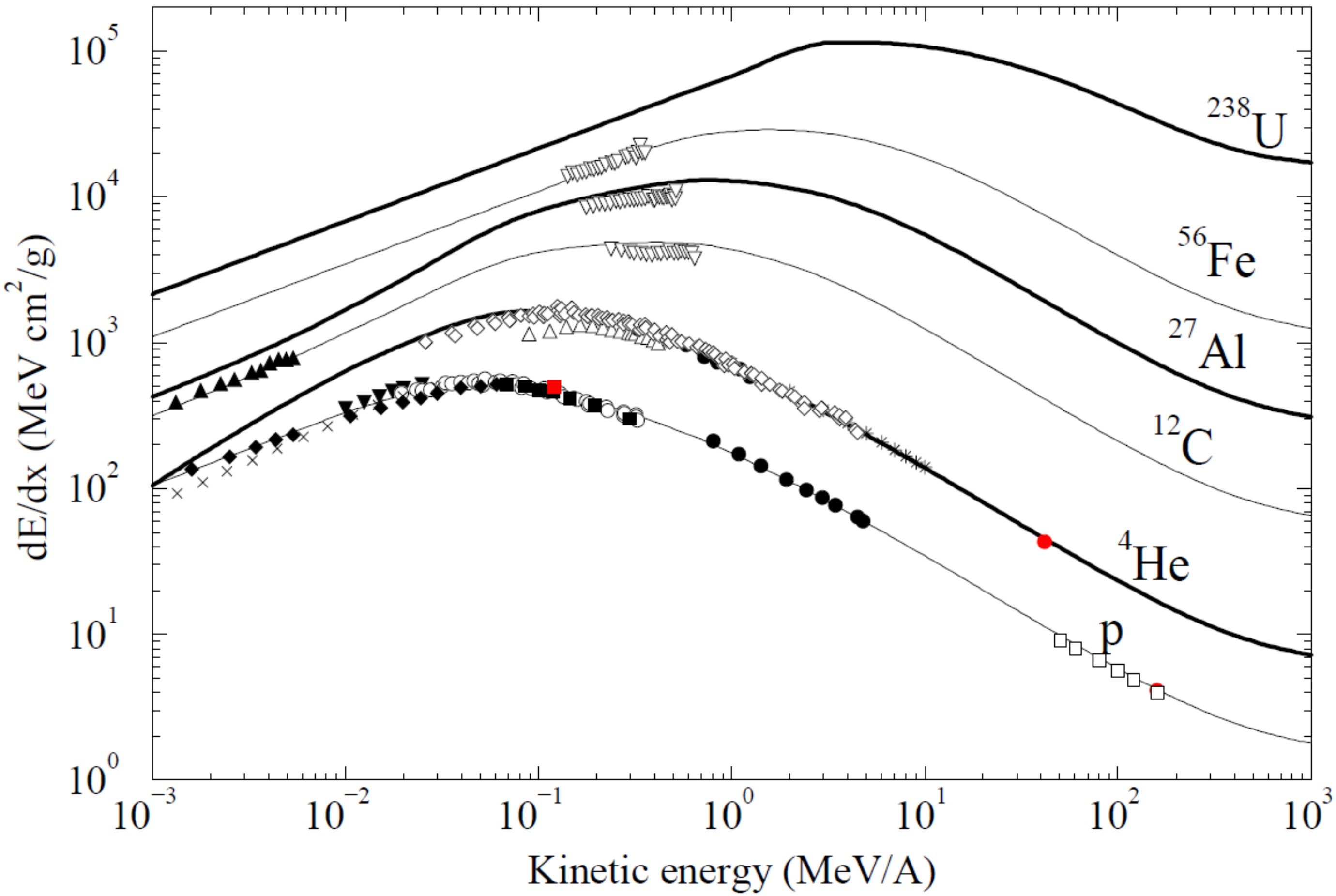
20x60cm Lead Cylinder



Accurate Description of Ion dE/dx down to 1 keV

Example: Ions in Si

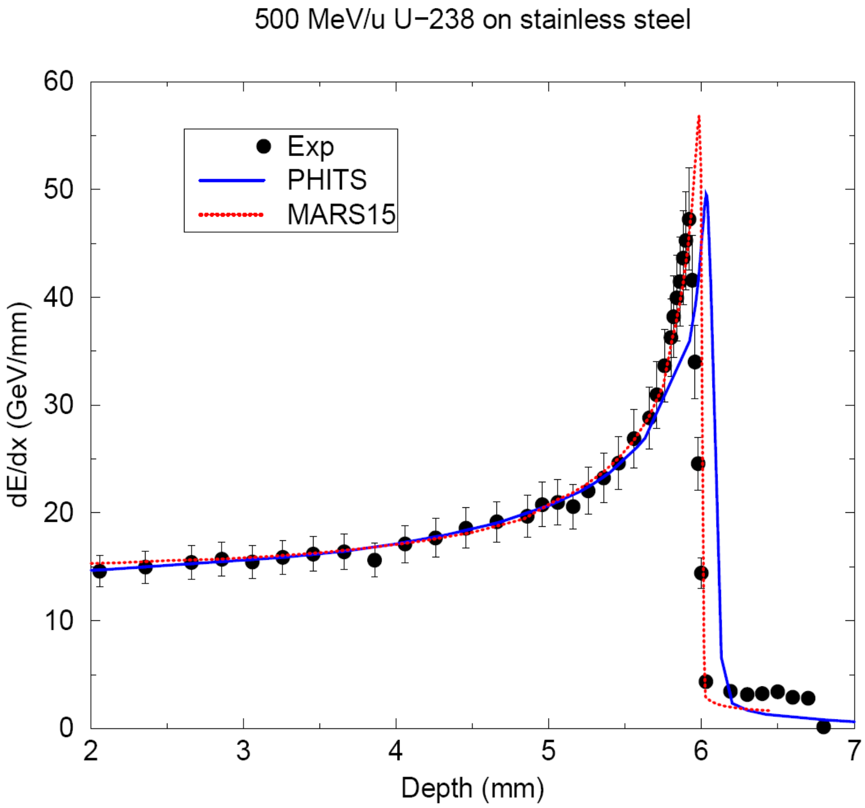
MARS15 vs data

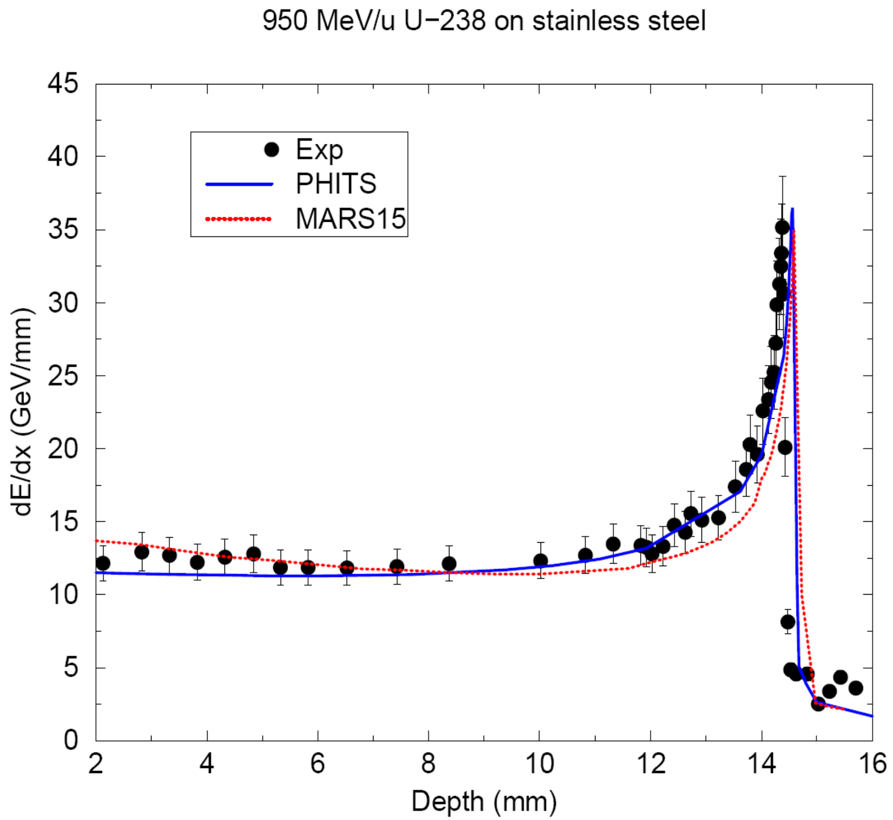


MARS15: fluctuations with correlated energy loss and Coulomb scattering

500 and 950 MeV/u U-238 on Stainless Steel

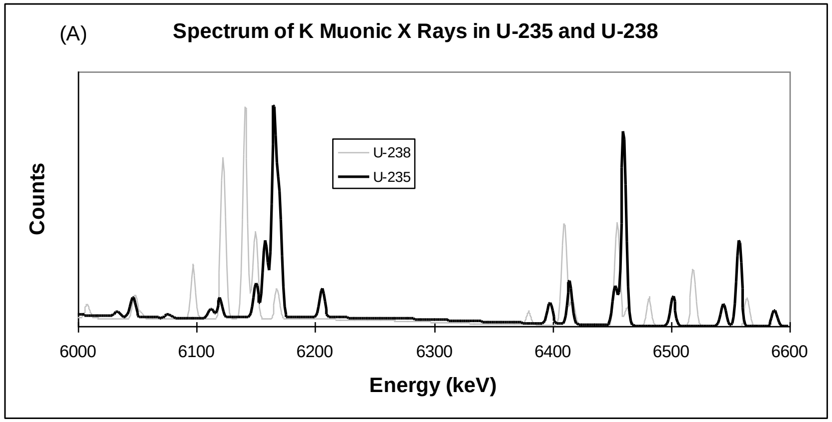
Accurate description of HI dE/dx down to keV in mixtures

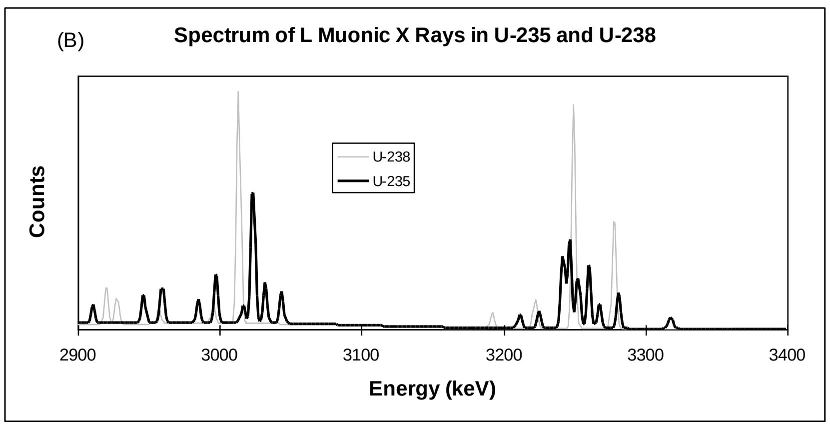




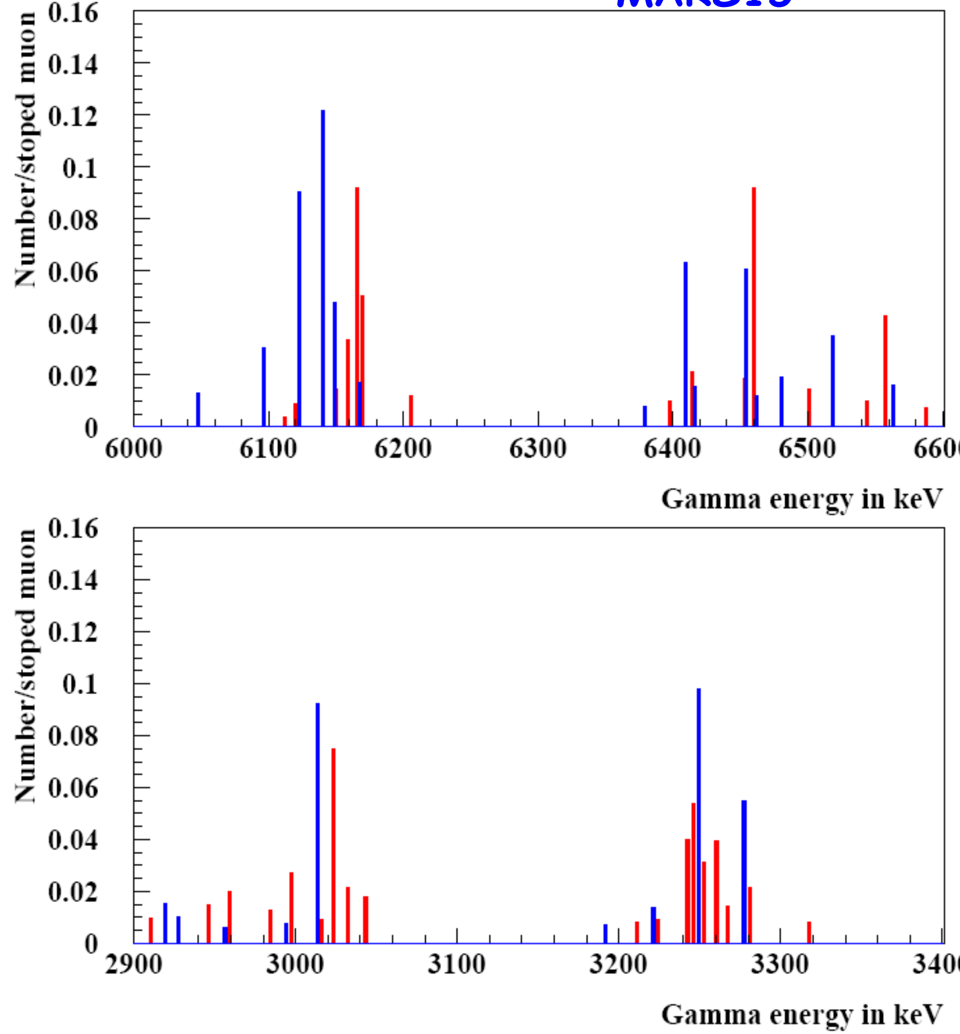
MARS15 and PHITS vs GSI data (2007)

Stopped Muons in Uranium: exp vs MARS15





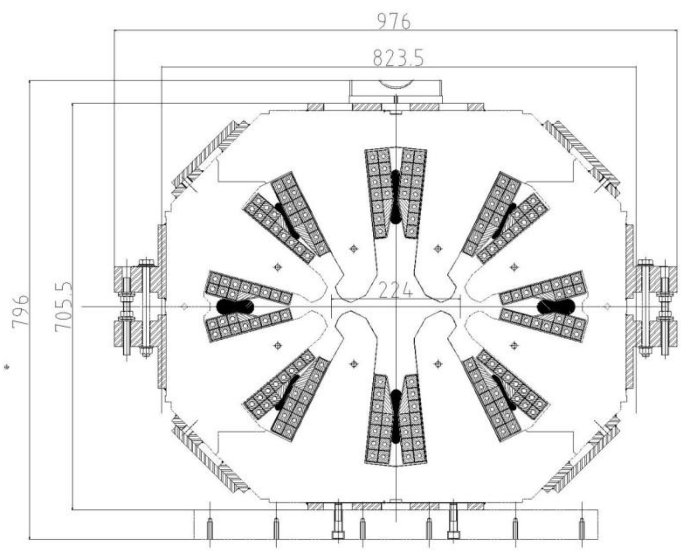
MARS15



X-rays at muon stop. Red - U^{235}. Blue - U^{238}.

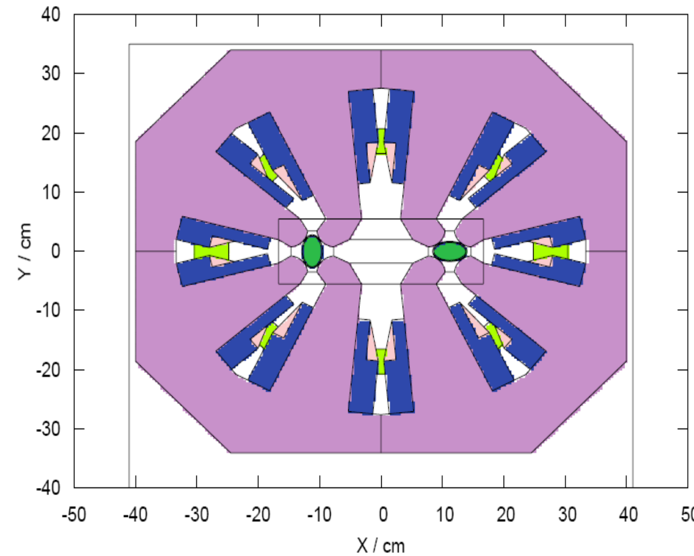
Experimental data on
μ^- cascade in U238 an U235

Technical Drawing → Implementation → MC Results

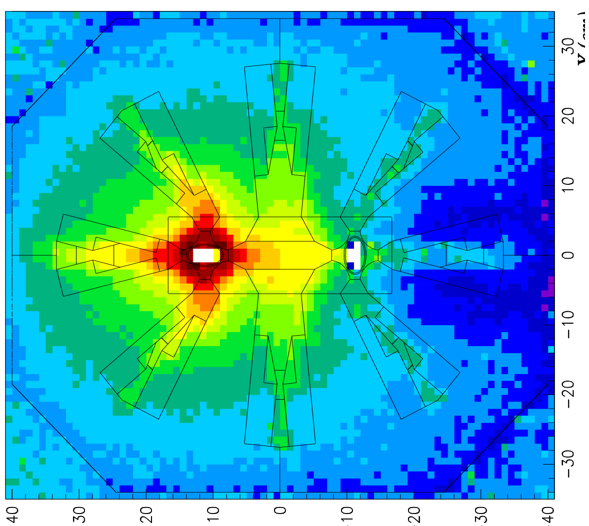


geometry

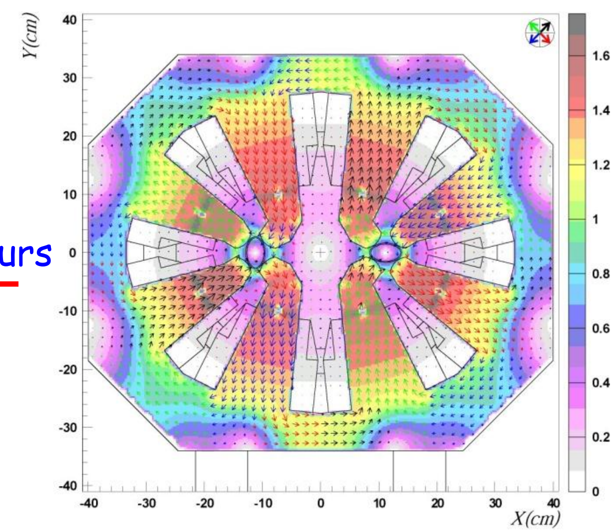
materials



magnetic field



calculated dose isocontours



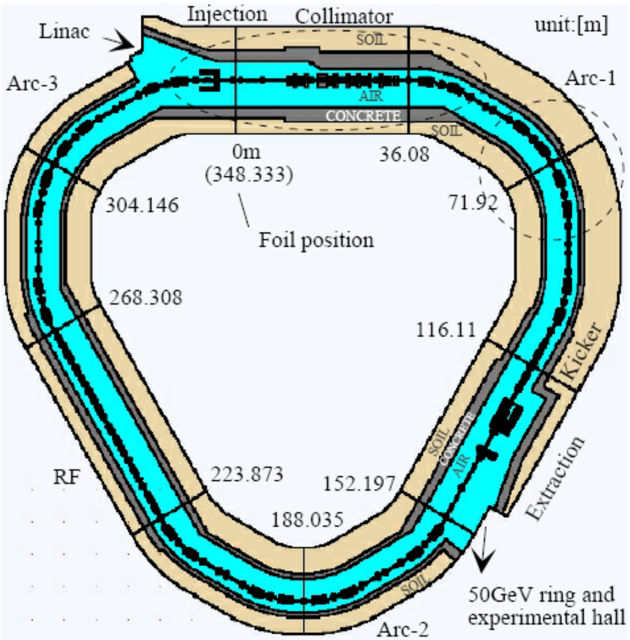
LHC MQW quadrupole in FLUKA

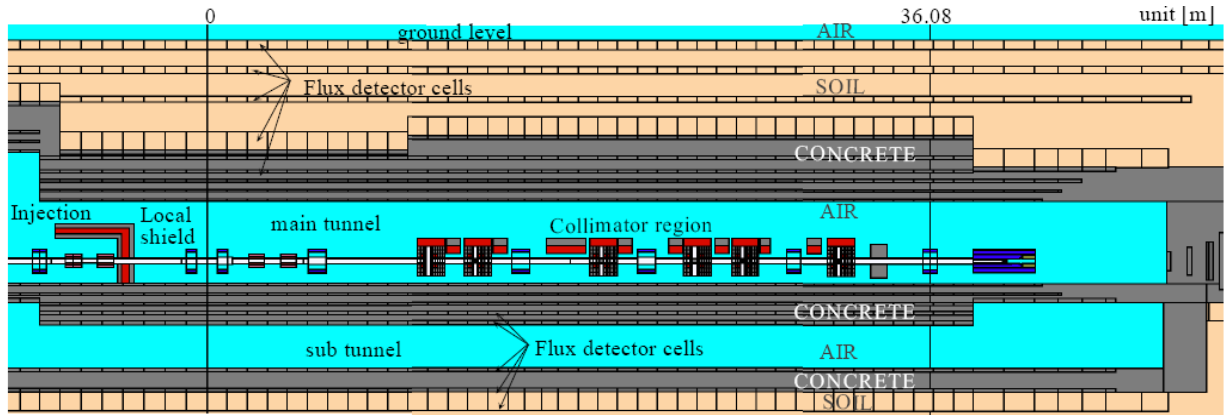
AUTOMATIC GEOMETRY GENERATION

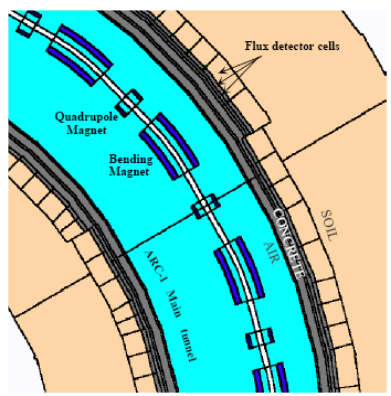
It is a modern approach for accelerator complexes like Tevatron, LHC and J-PARC to build a **realistic model of the whole machine** for multi-turn beam loss, energy deposition, activation and radiation shielding studies: read in **MAD lattice** and create a complete geometry and magnetic field model in the framework of such codes as FLUKA, MARS and GEANT.

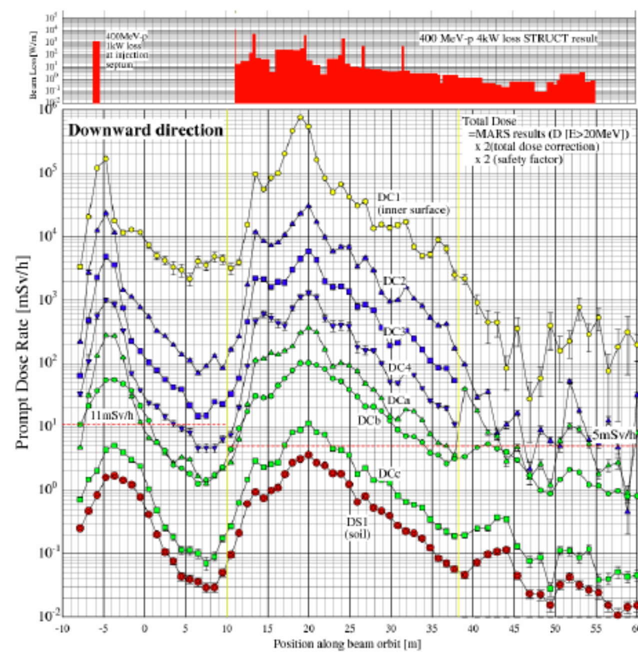
The experience says that such realistic modeling takes time and substantial efforts but always pays off.

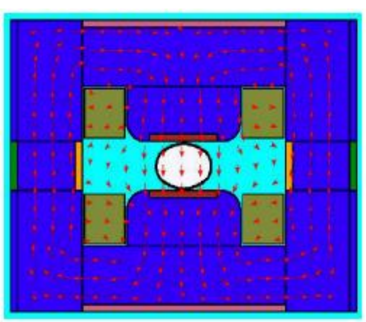
MAD-MARS BEAM LINE BUILDER: J-PARC 3-GeV RING

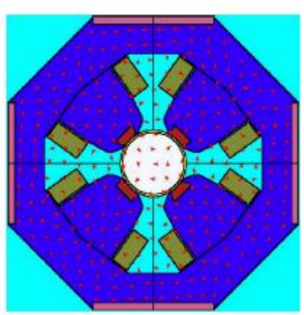






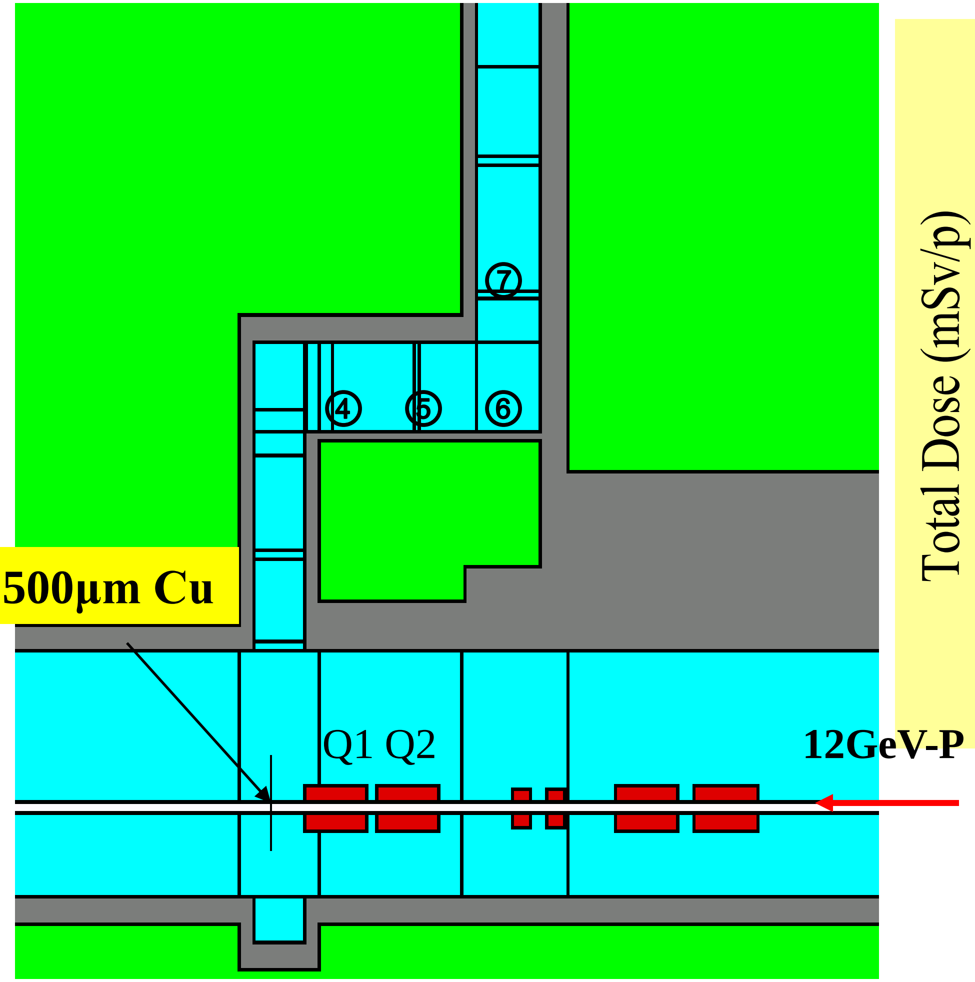


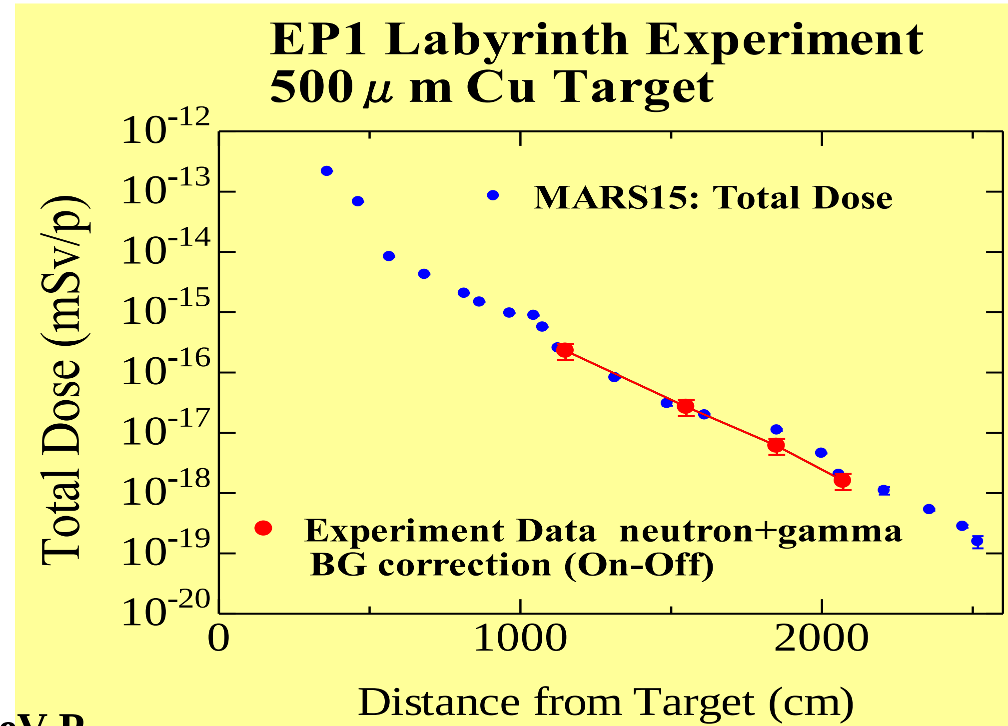




By N. Nakao

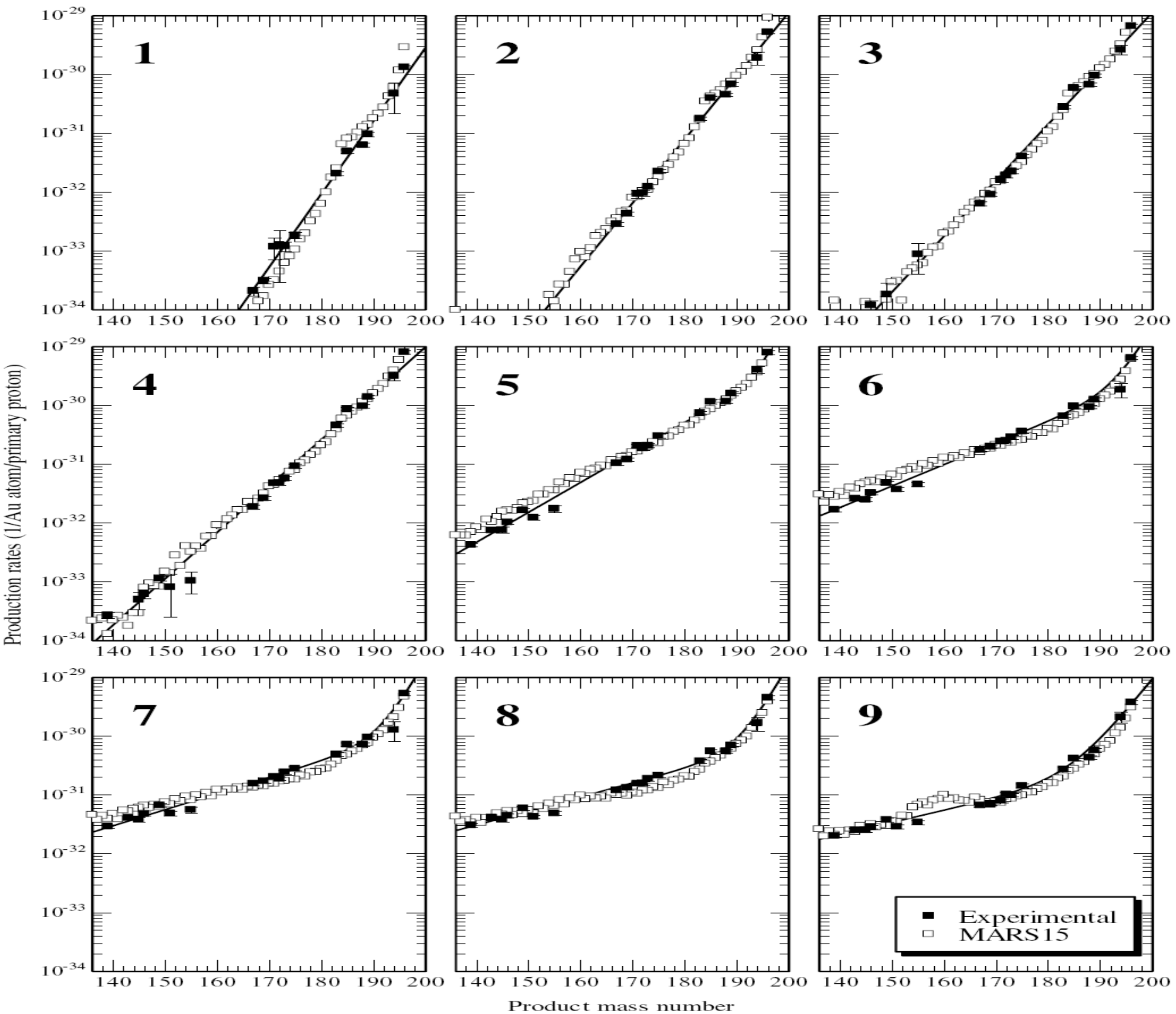
RECENT BENCHMARKING AT KEK: EP1 LABYRINTH

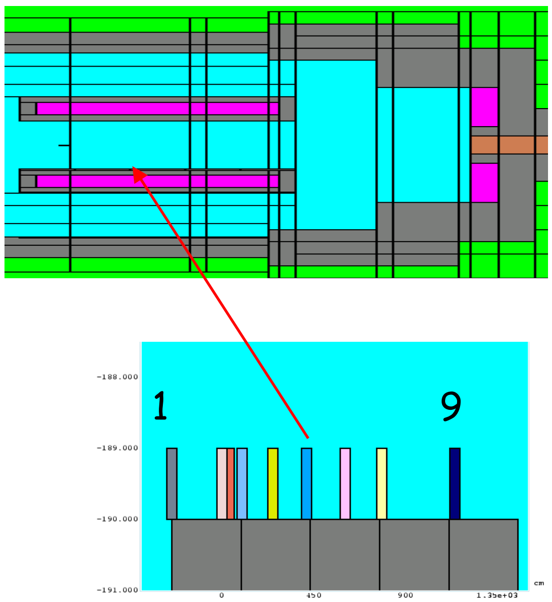




Courtesy: Takenori Suzuki

RECENT BENCHMARKING: 12-GeV K2K TARGET STATION

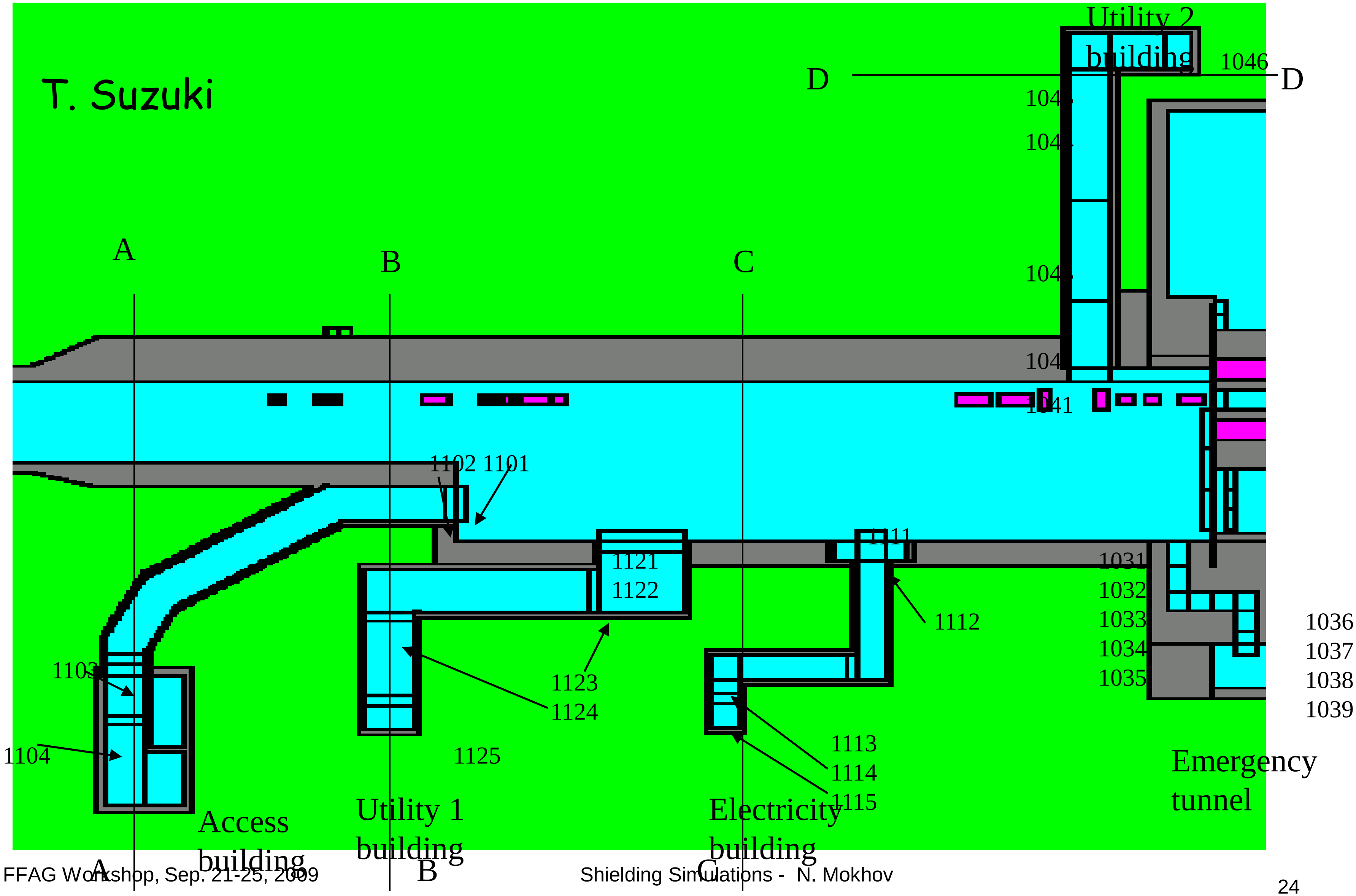




Nine gold foil samples over 12 meters

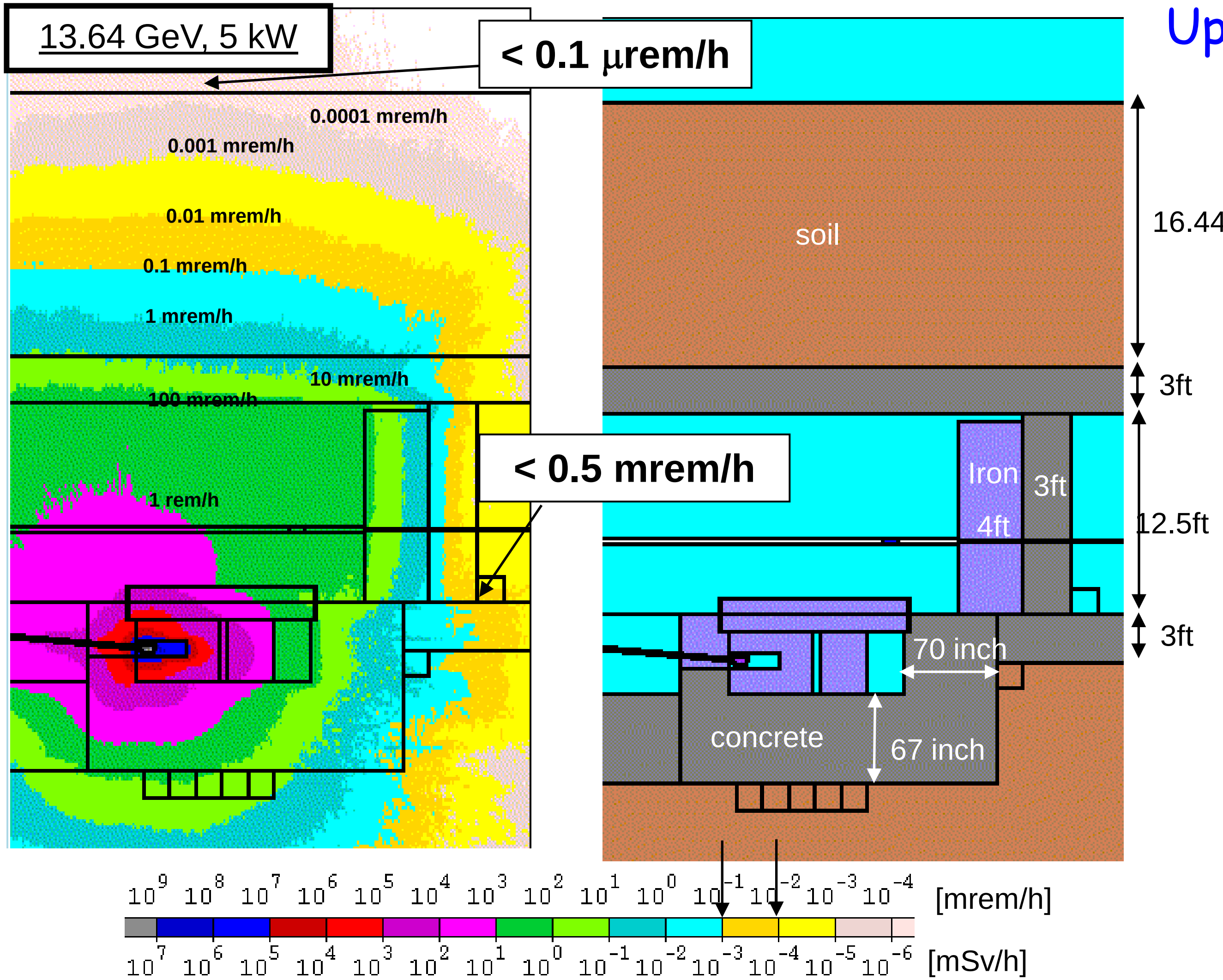
Courtesy: T. Suzuki and H. Matsumura

MARS15 Model og J-PARC Labyrinth Tunnel from Switchyard

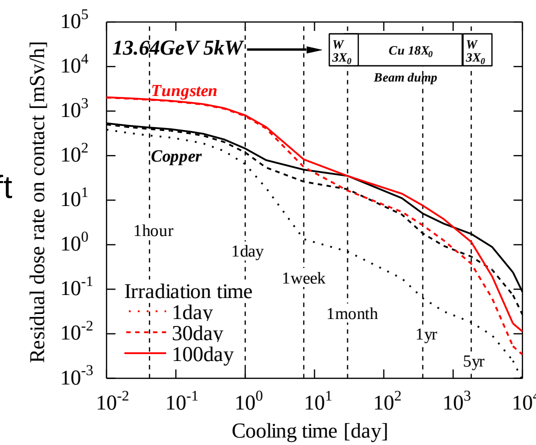


LCLS SHIELDING DESIGN WITH MARS15

Up to 16 GeV e-beam



Beam dump activation



By T. Sanami

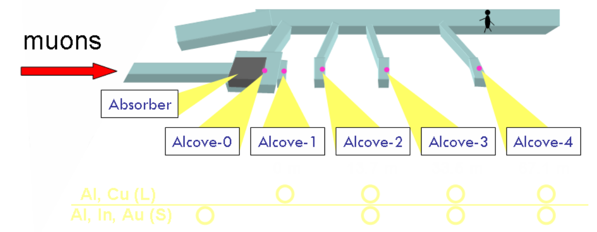
SHIELDING AND RADIATION EFFECT EXPERIMENT

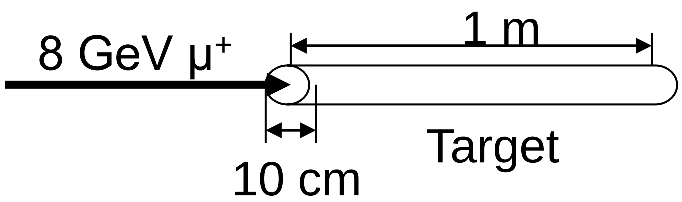
T972 Shielding and Radiation Effect Experiment at FNAL

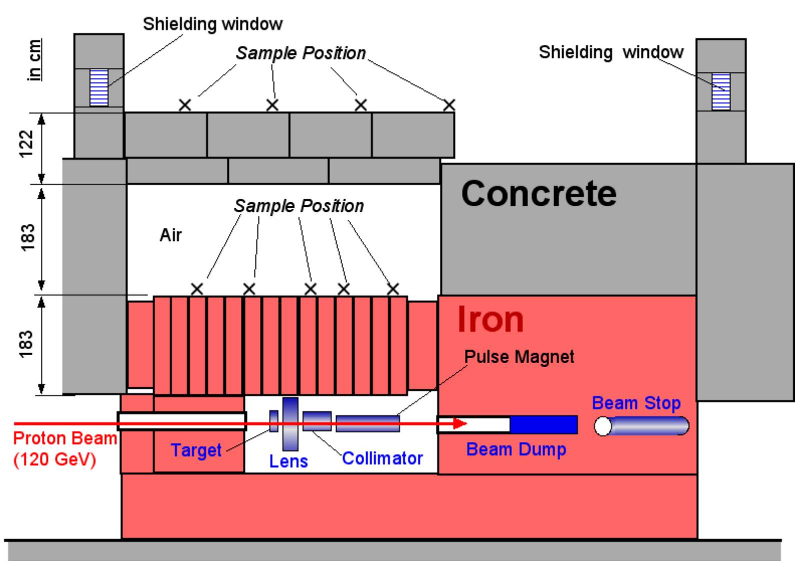
JASMIN Collaboration

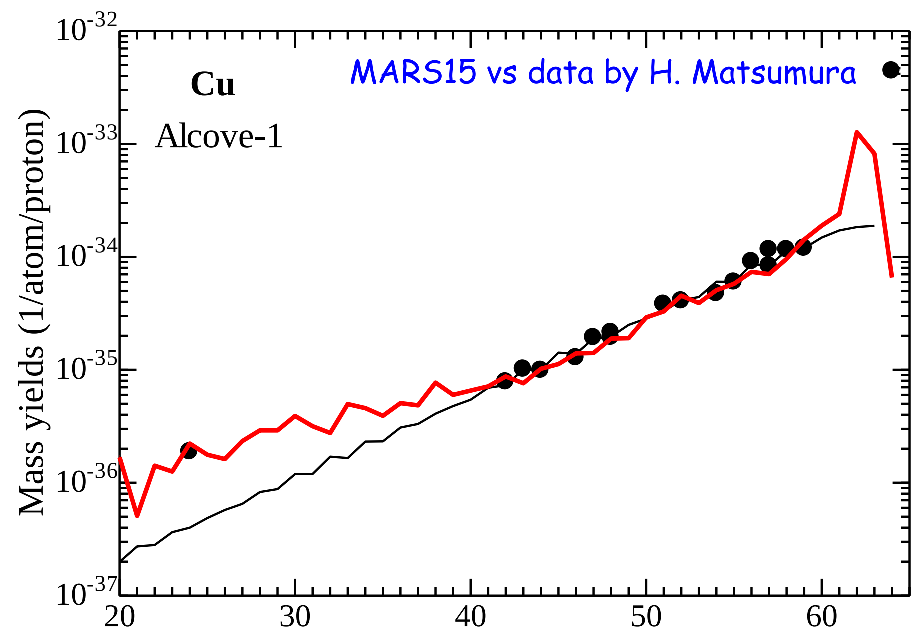
Shielding data and code benchmarking; targets, collimators and thick shields; radiation effects on instruments and materials. Started in fall 2007.

Example: Muon-induced nuclide production









Example: FRIB

A brand new project

"Facility for Rare Isotope Beams"

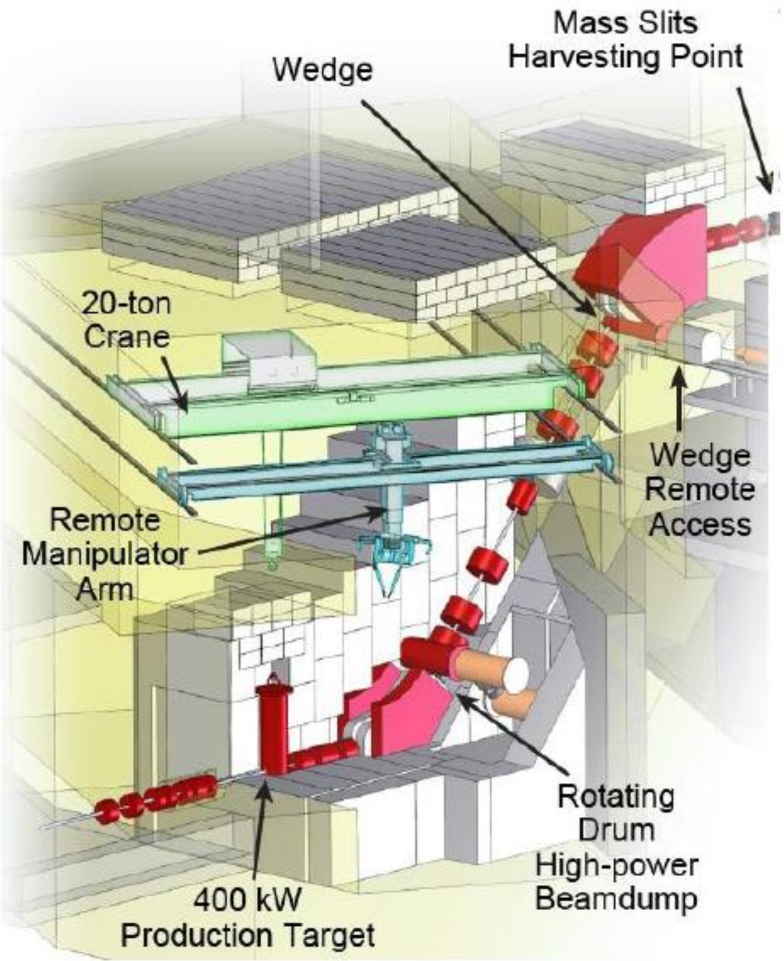
heavily relying on MARS15 and PHITS codes

in target and shielding designs

for up to 400 kW 400 MeV/A uranium beam

Target Facilities

- Scope
  - High-yield production of rare isotopes via in-flight production with light and heavy primary beams (400 kW, >200 MeV/u)
- Approach
  - Minimize risk; maximize safety and performance
- Technical Specifications
  - Self-contained new target building
    - » Keep most-activated and contaminated components in one spot
  - State-of-the-art full remote-handling
    - » Fast target changes
  - Target applicable to light and heavy beams
    - » Rotating solid-target concept
    - » Liquid Li target possible backup for heavy ions
  - Flexible upgrades, fast implementation
    - » ISOL stations or 2nd fragment separator
    - » Designed for 400 kW 400 MeV/u uranium



FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

05 - G. Bollen, 1 Sept 2009, Slide 4

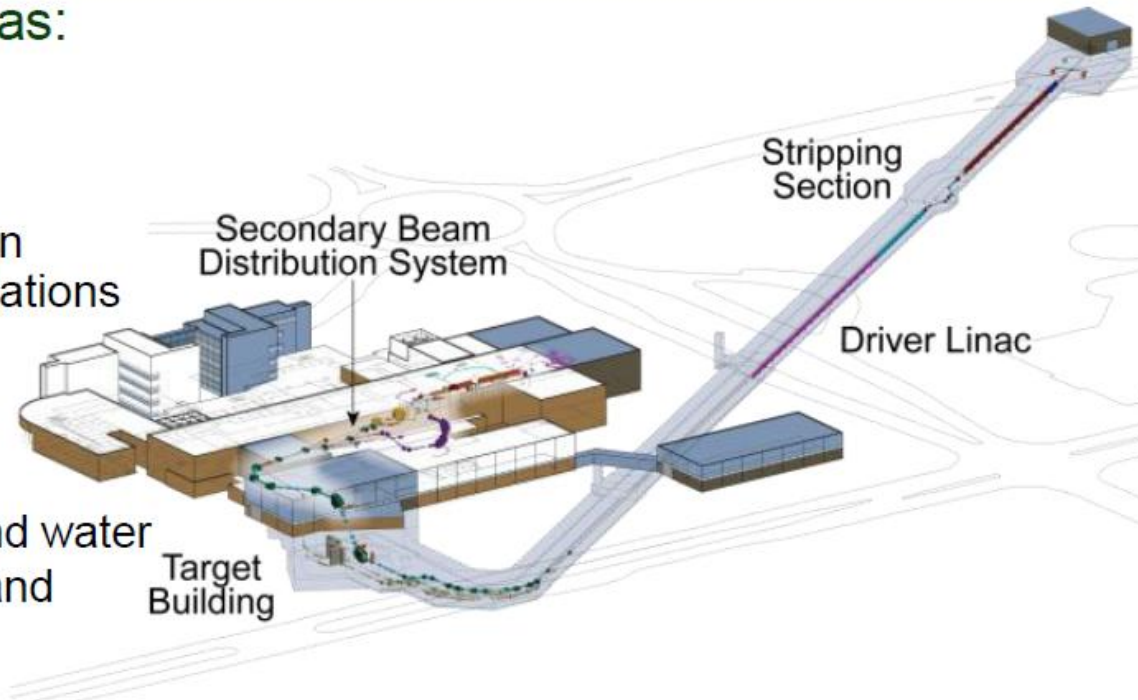
Scope of Radiation Transport Studies

Radiologically unique areas:

- Driver linac
- Stripping section
- Target building
- Secondary beam distribution system and experimental stations

Radiological aspects addressed by radiation transport:

- Activation of soil and ground water
- Activation of components and shielding
- Activation of air
- Prompt dose and neutron sky-shine
- Inventories
- Radiation damage / life-time
- Energy deposition



FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

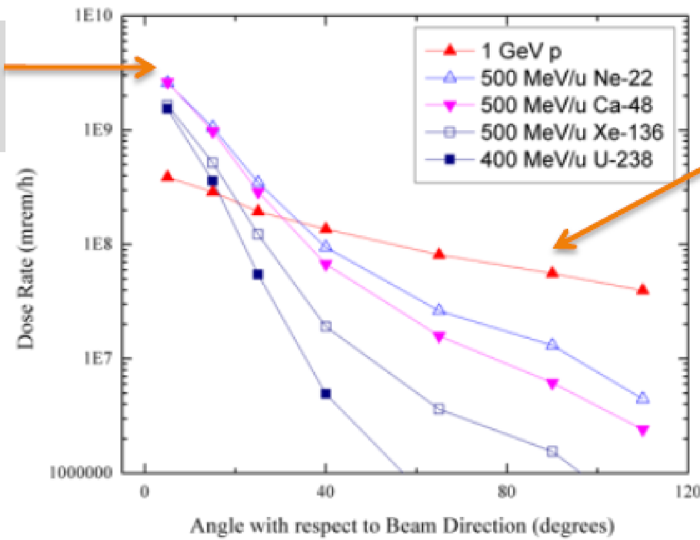
15 - M. Kostin, 2 Sept 2009, Slide 3

Assumptions in Radiation Transport (1)

- Radiation worker year - 2,000 hours
- Operational year - 5,555 hours (2×10^7 sec)
- Beam losses of 1 W/m during normal operation – driven by hands-on maintenance
- Bulk shielding calculations performed for worst beam scenarios

Dose equivalent rate outside of 1-meter concrete shielding (from PHITS)

400 kW, ^{48}Ca 500 MeV/u for the forward direction



400 kW, 1 GeV protons for the direction transverse to the beam

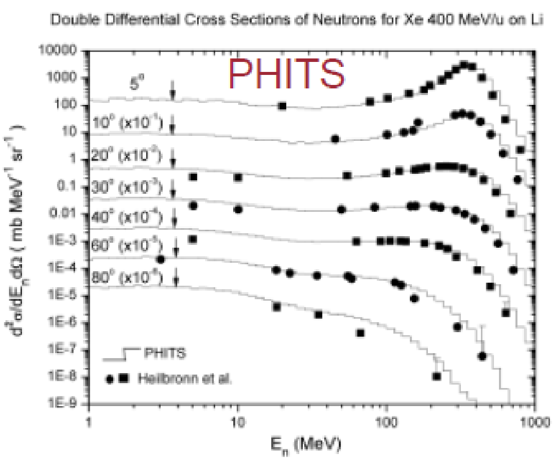
FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

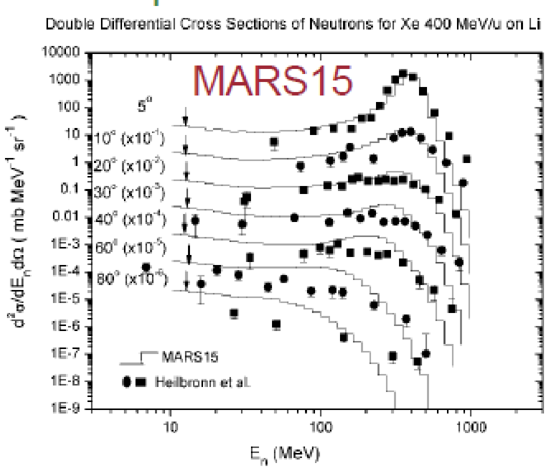
15 - M. Kostin, 2 Sept 2009, Slide 4

Approach and Tools

- For simple systems use Moyer model. Use radiation transport codes to verify.
- For more complicated cases use radiation transport codes, e.g. MARS15 for ISOL, PHITS for fragmentation target station
- MCNPX, FLUKA, GEANT other options, but not generally used
- Code benchmarking and validation
  - “Benchmarking Heavy Ion Transport Codes PHITS, FLUKA, HETC-HEDS, and MARS15” (**DE-FG02-08ER41548**)

Validation example: double differential neutron production cross sections



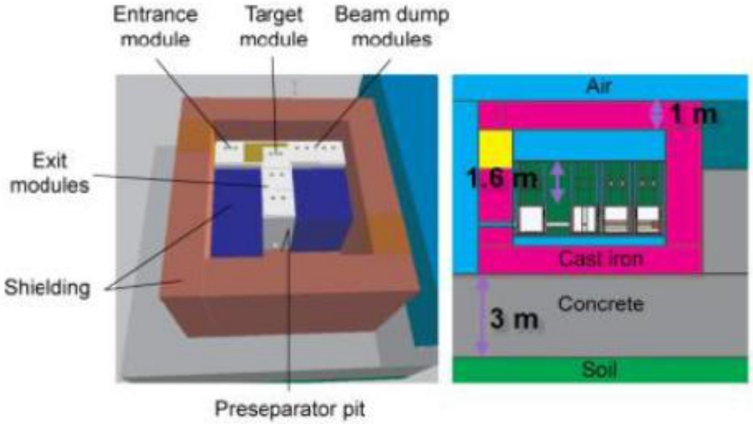


FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

15 - M. Kostin, 2 Sept 2009, Slide 6

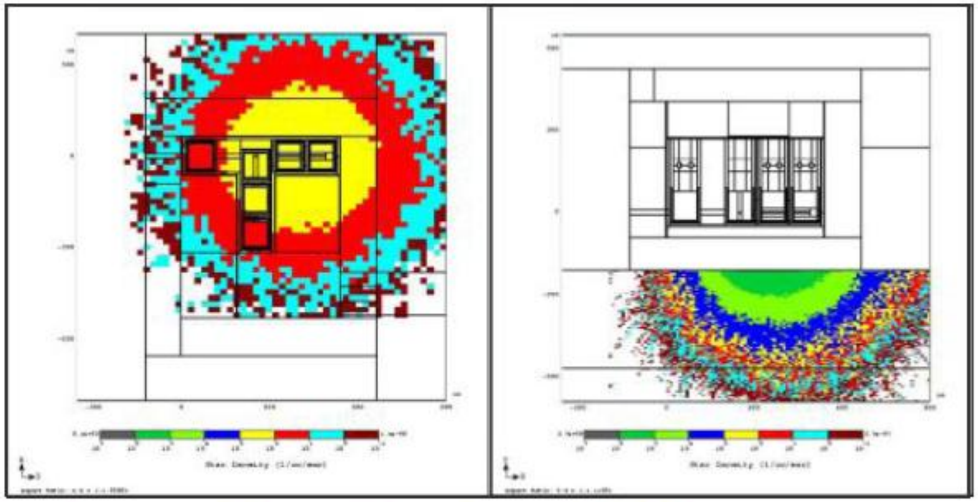
Ground Water Activation at ISOL Station

- Worst-case scenario considered – 1 GeV proton beam at 400 kW
- Geometry defined in MCNP format, calculations performed with MARS15



Star density in top 10 cm of soil

Star density in a vertical ± 20 cm layer



- Calculation of concentrations of the dominant radionuclides ^{3}H and ^{22}Na performed using FNAL Concentration Model
- 2 meters of cast iron and 3 meters of regular concrete required under the target station

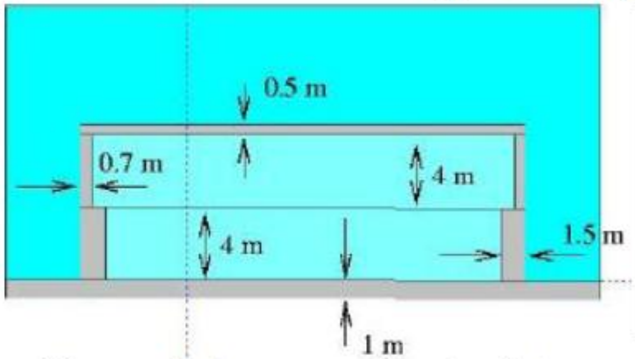
FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

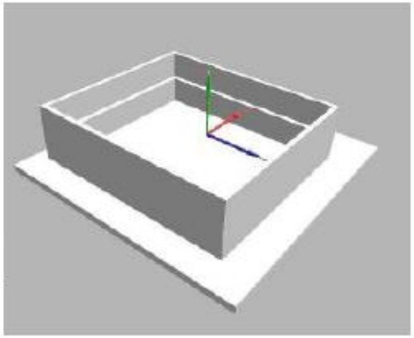
15 - M. Kostin, 2 Sept 2009, Slide 13

Scoping Study for Neutron Sky-Shine (Target Area)

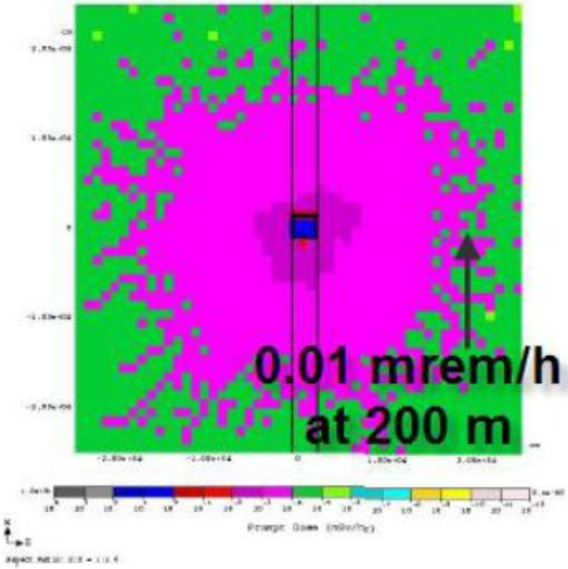
- Neutrons are reflected from atmosphere – neutron sky-shine
- Model: ground, target building, and surrounding air 5 km x 5 km x 2.5 km (vertical direction). 2.5 km is more than 3 interaction lengths for neutrons.
- Neutrons flux from previously shown ISOL target station model used as input
- No moisture in the air and no air density variation with the height considered

Target building model





500 m x 500 m area



- Prompt dose equivalent drops ≈10 times every 500 m
- Prompt dose equivalent would be 55 mrem/y at 200 m
  - Necessary additional shielding can be easily provided, for example by adding 1 meter of iron to ISOL target modules

FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

15 - M. Kostin, 2 Sept 2009, Slide 14

SUMMARY

- Nowadays, there are several Monte-Carlo codes around which allow to address most of the challenging issues in R&D and design of radiation shielding, targets, collimators, dose to patients, nuclide production and alike for proton, electron and heavy-ion beams, with impressive results obtained over last years.
- Results of benchmarking of those widely-used codes are quite encouraging, and in some cases helped reveal existing inconsistencies.
- Some problems/difficulties in the codes are still exist, requiring further developments.